Antimatter Gravity with Muons

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Astrophysics Seminar
Fermilab
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Outline

- Motivation
- Experimental approach
- Required R&D
- Conclusions

Motivation in a Nutshell

- Standard cosmology has (at least) 4 major anomalies — and *introduces a new effect* to explain each!
  - horizon and flatness problems: inflation
  - cosmic acceleration: dark energy
  - galactic rotation curves: dark matter
  - baryon asymmetry: non-SM CP violation

Motivation in a Nutshell

- But what if matter and antimatter repel gravitationally?
  - leads to universe with separated matter and antimatter regions (and implies ∃ gravitational dipoles)

    [M. M. Nieto & T. Goldman, "The Arguments Against 'Antigravity' and the Gravitational Acceleration of Antimatter," Phys. Rep. 205 (1991) 221]
    - baryon asymmetry could be local, not global ⇒ no need for new CPV sources

      [A. Benoit-Lévy and G. Chardin, "Introducing the Dirac-Milne universe," Astron. & Astrophys. 537 (2012) A78]
  - repulsion changes expansion rate of universe
    - possible explanation for apparent acceleration – without dark energy

      [D. Hajdukovic, "Quantum vacuum and virtual gravitational dipoles: the solution to the dark energy problem?," Astrophys. Space Sci. 339 (2012) 1]
    - all regions of early universe causally connected – no need for inflation

      [A. Benoit-Lévy and G. Chardin, *ibid.*]
  - virtual gravitational dipoles strengthen gravity at long distances
    - possible explanation for rotation curves – without dark matter

      [L. Blanchet, "Gravitational polarization and the phenomenology of MOND," Class. Quant. Grav. 24, 3529 (2007);
      L. Blanchet & A.L. Tiec, "Model of dark matter and dark energy based on gravitational polarization," PRD 78, 024031 (2008)]

Motivation in a Nutshell

- An even more radical view:

[D. Hajdukovic, "Virtual gravitational dipoles: The key for the understanding of the Universe?," Physics of the Dark Universe 3 (2014) 34–40]

- Sea of virtual gravitational dipoles *is* the dark energy
- As universe expands, virtual grav. dipole sea reaches saturation and ceases to exert pressure
- Subsequent collapse creates *enormous* black hole spewing antimatter
  - thus next cycle of expansion & collapse is *antimatter* universe
  - & so on…

Motivation in a Nutshell

- More generally, unclear whether Lorentz and CPT symmetry are perfect, or only approximate
  - many symmetries are only approximate:
    - isospin, parity, CP, T, lepton flavor,…
  - searching for and studying small violations has often been a fruitful way forward → "Standard Model Extension" (SME)
- Antimuon gravity can access unique SME coefficients

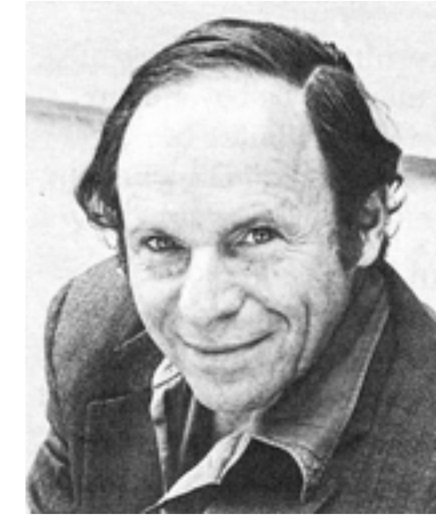
[V. A. Kostelecky & J. D. Tasson, "Matter-Gravity Couplings and Lorentz Violation," Phys. Rev. D 83, 016013 (2011)]

  - via small deviations from $\overline{g}$ = g, or sidereal variation
- *Only way* to access gravitational coupling to 2nd gen.
- *And* generically sensitive to possible 5th forces

Historical Note…

- 1955: $\bar{p}$ discovery at Berkeley Bevatron
- Already in 1956, M. Goldhaber noted the "baryon asymmetry of the universe" (BAU) [M. Goldhaber, "Speculations on Cosmogeny," Science 124 (1956) 218]
  - universe seems to contain *lots* of mass in the form of baryons – protons and neutrons – but almost *no* antimatter! How could this be consistent with the BB?
  - now generally believed BAU arose through *CP violation* (discovered in 1964)
  - but, pre-1964, more plausible to postulate *gravitational repulsion* between matter and antimatter – "antigravity"!

Am. J. Phys. **26** (1958) 358



Approximate Nature of Physical Symmetries*

P. Morrison
Cornell University, Ithaca, New York
(Received May 21, 1958)

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[...] For there is no more evident failure of symmetry in the world we see about us than the failure of charge conjugation. Matter made of particles, protons, electrons, and neutrons, is all about, but antimatter, made of antiparticles, is nowhere to be found. It is none the less possible to manufacture it, but only at great expense. If we committed the whole United States Federal Budget, Department of Defense and all, to the buying of antimatter at present prices, we could own a single microgram of the stuff only after we had paid off installments for a thousand years! [...]

Many have argued against the existence of antigravity, but they have all *postulated* the equivalence principle. It is evident that the Berkeley experiments prove the positive inertial mass of the antinucleon; it costs positive energy to make one. Then, if the gravitational mass is to be negative, the equivalence principle must break down. It will hold well enough as an approximation if test bodies and sources of field alike all are exclusively made of nucleons, and contain no antinucleons. That is our present situation. On this view a proton falls, but an antiproton *rises* in the earth's gravitational field. [...]

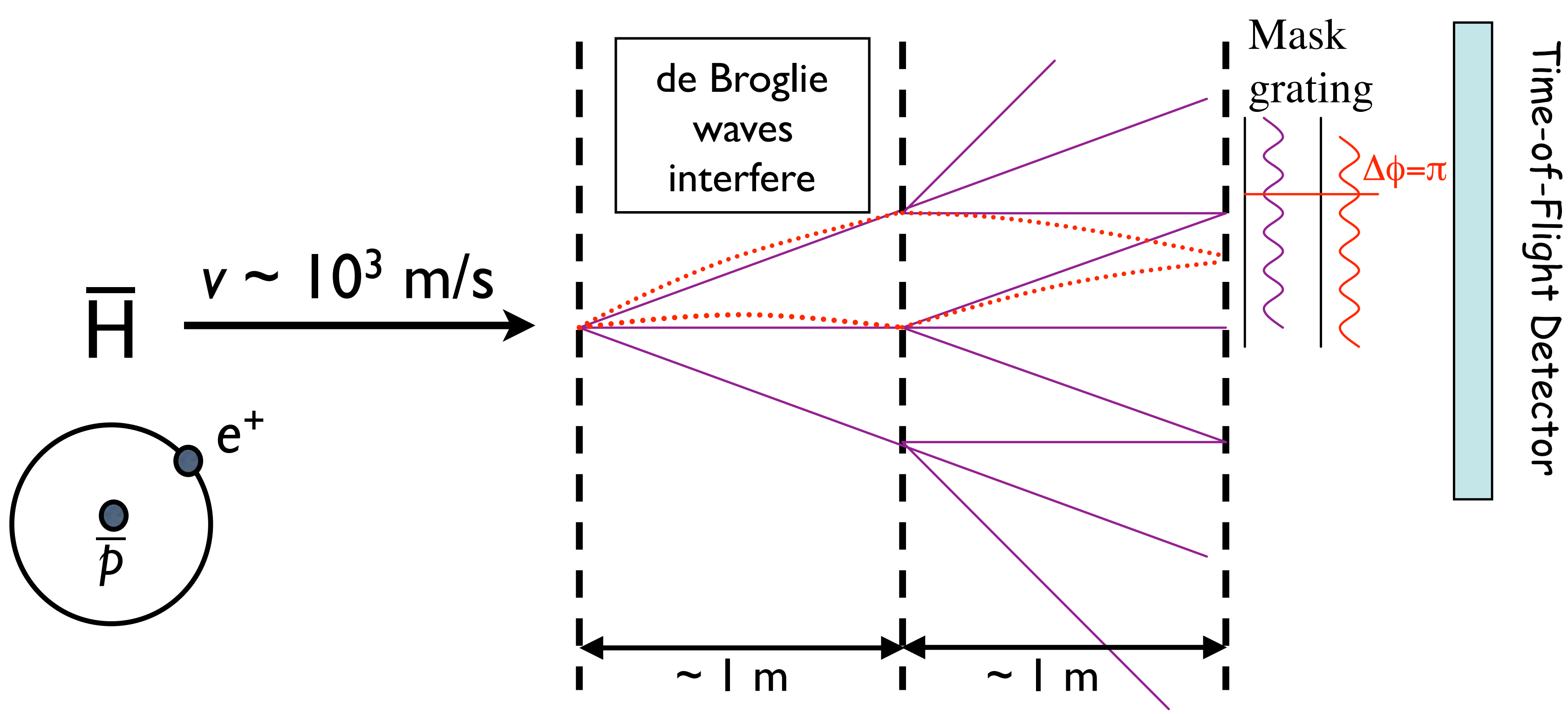
- Equivalence Principle is *fundamental* to General Relativity
  - if it doesn't apply to antimatter, at the very least, our understanding of GR must be modified…

Studying Antimatter Gravity

- How might it be tested experimentally?
- Clear that one needs *neutral* antimatter –
  - otherwise gravity's tiny effect swamped by residual EM forces
  - has led to multiple *antihydrogen* ($\overline{\mathrm{H}}$) gravity efforts in progress at CERN AD (ALPHA, ATRAP, ASACUSA, AEgIS, GBAR)

Studying Antimatter Gravity

- In principle a simple interferometric measurement with slow antihydrogen beam [T. Phillips, Hyp. Int. 109 (1997) 357]:



$\frac{1}{2}\, gt^2 = 5\ \mu\text{m}$

- But that's not how anybody's actually *doing* it!

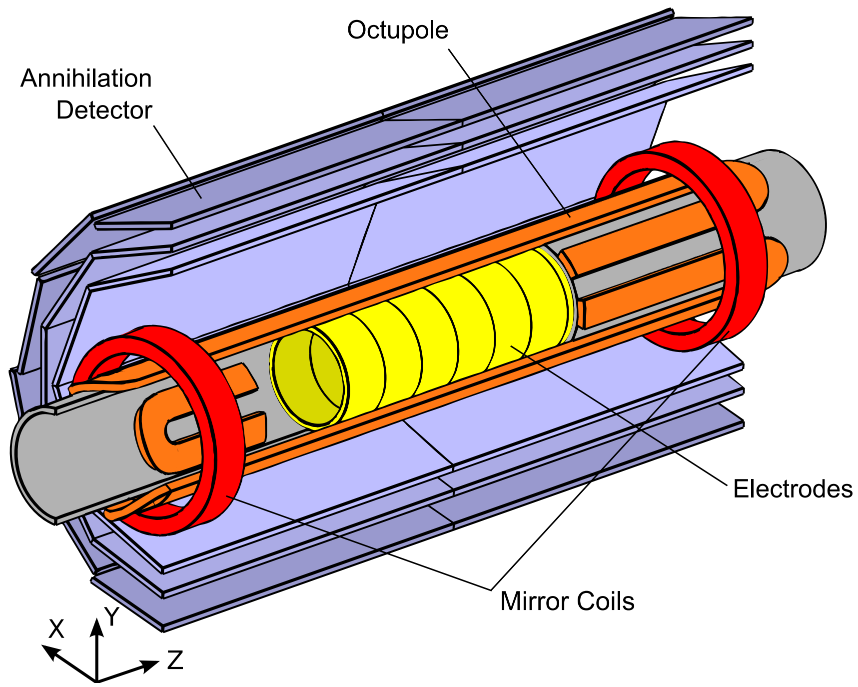
Studying Antimatter Gravity

- World leader: ALPHA* at CERN Antiproton Decelerator

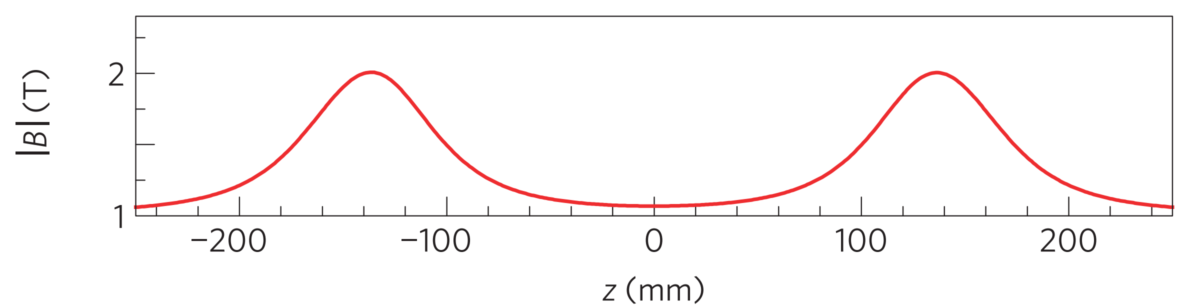
  * Antihydrogen Laser Physics Apparatus

Aarhus Univ, Simon Fraser Univ, Berkeley, Swansea Univ, CERN, Univ Federal do Rio de Janeiro, Univ of Calgary, TRIUMF, Univ of British Columbia, Univ of Tokyo, Stockholm Univ, York Univ, Univ of Liverpool, Univ of Victoria, Auburn Univ, NRCN-Nuclear Research Center Negev, RIKEN

- They've made antihydrogen from $\bar{p}$ and e+ in a Penning trap and trapped it with an octupole winding,



[G. B. Andresen et al., "Confinement of antihydrogen for 1,000 seconds," Nature Phys. 7 (2011) 558]



- then shut off the magnet currents to see whether more $\overline{\mathrm{H}}$ annihilate on the top or on the bottom

[C. Amole et al., "Description and first application of a new technique to measure the gravitational mass of antihydrogen," Nature Comm. 4 (2013) 1785]

Studying Antimatter Gravity

- The first published limit:
- Let $F = m_{grav.}/m_{inert.}$ of $\bar{\mathrm{H}}$
- Then

$$-65 \leq F \leq 110 \text{ @ } 90\% \text{ C.L.}$$

[ALPHA Collaboration, 2013]

- They propose improving sensitivity to $\Delta F \sim 0.5$
- May take 5 years…?

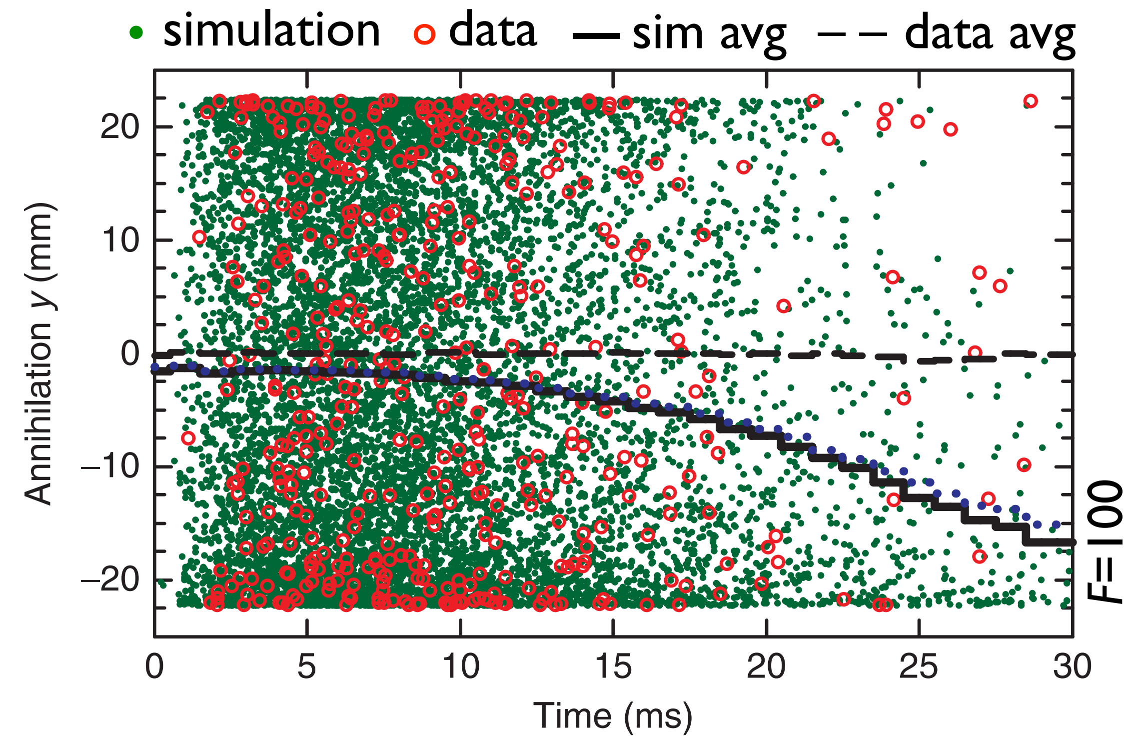


Figure 2 | Annihilation locations. The times and vertical (y) annihilation locations (green dots) of 10,000 simulated antihydrogen atoms in the decaying magnetic fields, as found by simulations of equation 1 with $F=100$. Because $F=100$ in this simulation, there is a tendency for the anti-atoms to annihilate in the bottom half ($y<0$) of the trap, as shown by the black solid line, which plots the average annihilation locations binned in 1 ms intervals. The average was taken by simulating approximately 900,000 anti-atoms; the green points are the annihilation locations of a sub-sample of these simulated anti-atoms. The blue dotted line includes the effects of detector azimuthal smearing on the average; the smearing reduces the effect of gravity observed in the data. The red circles are the annihilation times and locations for 434 real anti-atoms, as measured by our particle detector. Also shown (black dashed line) is the average annihilation location for $\sim$840,000 simulated anti-atoms for $F=1$.

[C. Amole et al., "Description and first application of a new technique to measure the gravitational mass of antihydrogen," Nature Comm. 4 (2013) 1785]

Studying Antimatter Gravity

- How might it be tested experimentally?
- Clear that one needs *neutral* antimatter –
  - otherwise gravity's tiny effect swamped by residual EM forces
  - has led to multiple *antihydrogen* ($\overline{\text{H}}$) gravity efforts in progress at CERN AD (ALPHA, ATRAP, ASACUSA, AEgIS, GBAR)
    - but $\overline{\text{H}}$ hard to produce and manipulate!
    - antiprotons required ⇒ possible only at AD
- However – another approach may also be feasible...

Studying Antimatter Gravity

- Besides antihydrogen, only *one* (or 2?) *other* antimatter system conceivably amenable to gravitational measurement:
- Muonium (M or Mu) —
  - a hydrogenic atom with a positive (anti)muon replacing the proton
    - easy to produce but hard to study
- Measuring muonium gravity — if feasible — could be the *first* gravitational measurement of a lepton, and of a 2^{nd}-generation particle

Studying Muonium Gravity

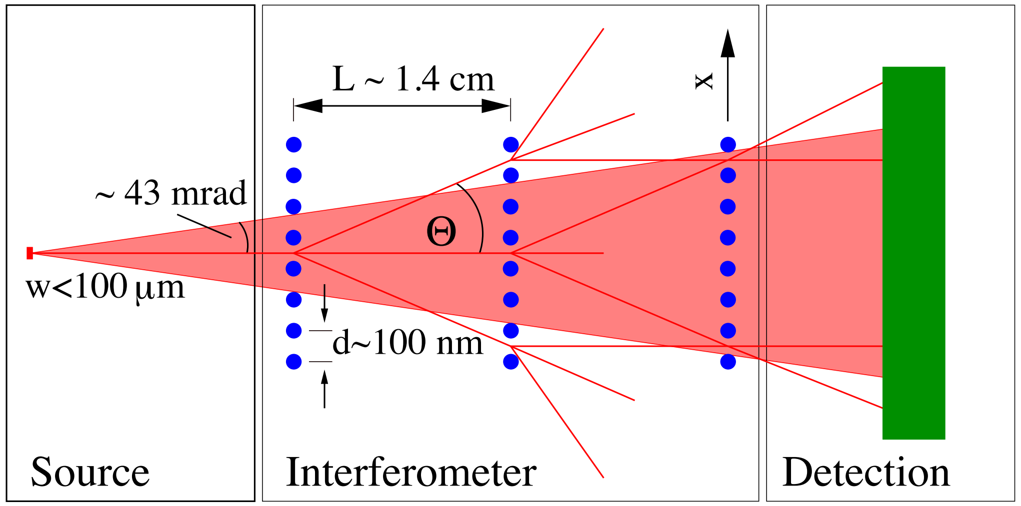
arXiv:physics/0702143v1 [physics.atom-ph]

Testing Gravity with Muonium

K. Kirch*
Paul Scherrer Institut (PSI), CH-5232 Villigen PSI, Switzerland

(Dated: February 2, 2008)

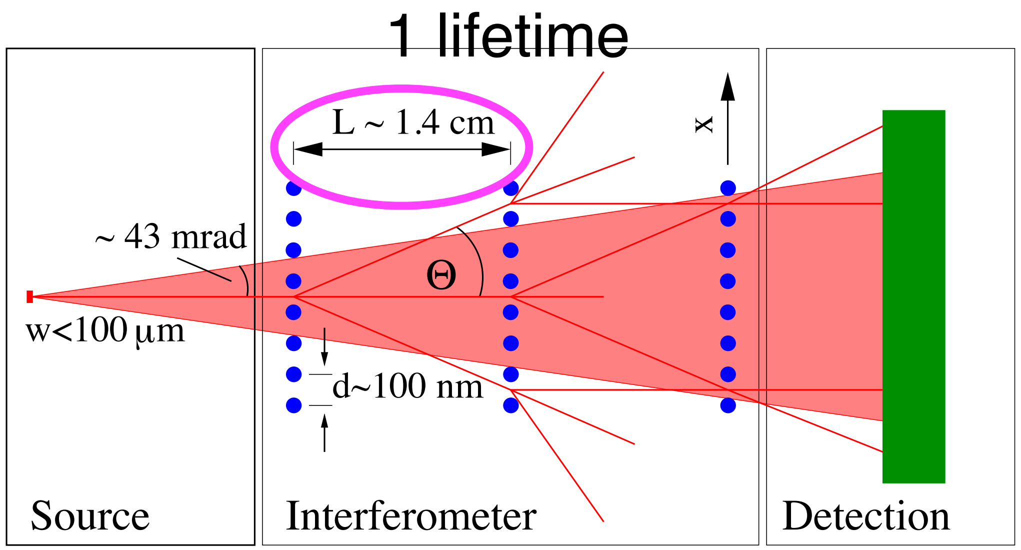
Recently a new technique for the production of muon (μ^+) and muonium (μ^+e^-) beams of unprecedented brightness has been proposed. As one consequence and using a highly stable Mach-Zehnder type interferometer, a measurement of the gravitational acceleration $\bar{g}$ of muonium atoms at the few percent level of precision appears feasible within 100 days of running time. The inertial mass of muonium is dominated by the mass of the positively charged - antimatter - muon. The measurement of $\bar{g}$ would be the first test of the gravitational interaction of antimatter, of a purely leptonic system, and of particles of the second generation.



Studying Muonium Gravity

- Adaptation of T. Phillips' $\bar{\mathrm{H}}$ interferometry idea to an antiatom with a 2.2 μs lifetime! [T. Phillips, "Antimatter gravity studies with interferometry," Hyp. Int. 109 (1997) 357]

$v \approx 6300$ m/s



$\frac{1}{2} gt^2 = 24$ pm

Smaller than hydrogen atom!

- "Same experiment" as Phillips proposed — only harder!
- Is it feasible?
  - how might it be done?

Studying Muonium Gravity

- Part of the challenge is the M production method:
  - need *monoenergetic* M so as to have uniform flight time
    - otherwise the interference patterns of different atoms will have differing relative phases,
  - so the signal will be washed out

Monoenergetic Muonium?

- Proposal by D. Taqqu of Paul Scherrer Institute (Switzerland):

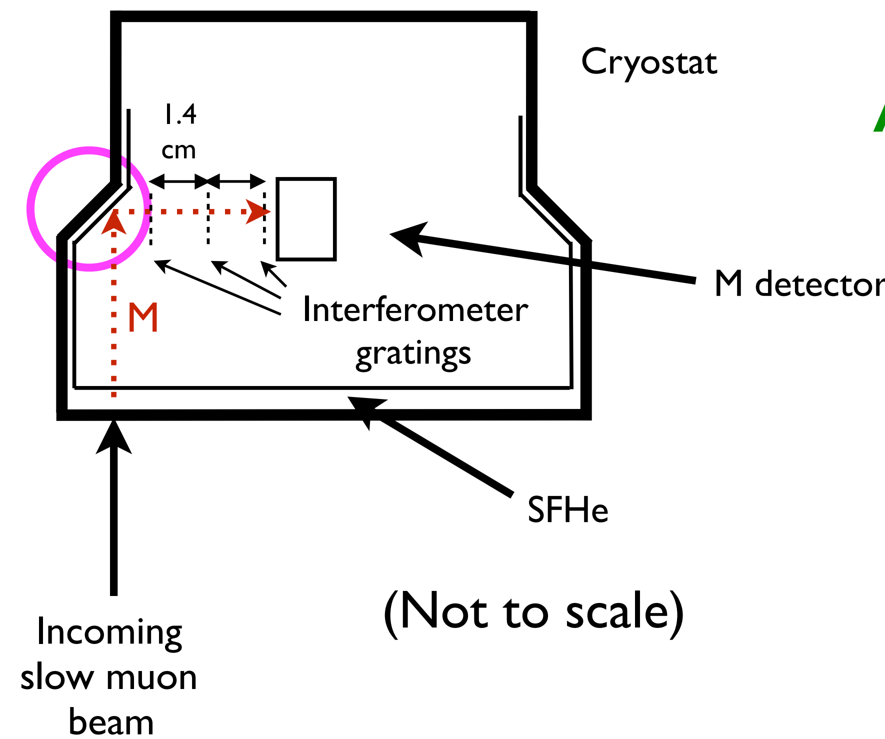
[D. Taqqu, "Ultraslow Muonium for a Muon beam of ultra high quality," Phys. Procedia 17 (2011) 216]

  - stop slow (eV) muons in μm-thick layer of superfluid He (SFHe)
  - chemical potential of hydrogen in SFHe will eject M atoms at 6,300 m/s, perpendicular to SFHe surface
    - makes ≈ monochromatic beam!

$$\Delta E/E \approx 0.2\%$$

Muonium Gravity Experiment

- One can then imagine the following apparatus:



A "ship in a bottle!"

Sensitivity estimate @ 100 kHz:

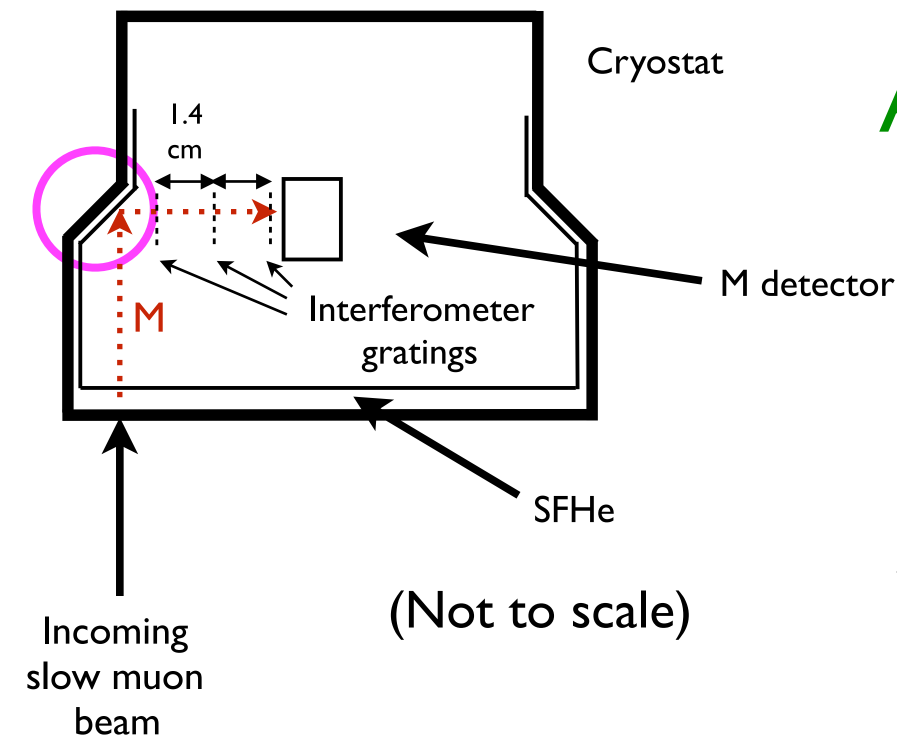
$$S = \frac{1}{C\sqrt{N_0}}\frac{d}{2\pi}\frac{1}{\tau^2}$$
$$\approx 0.3\,\mathrm{g}\ \ \mathrm{per}\ \sqrt{\#\mathrm{days}}$$

- Well known property of SFHe to coat surface of its container

- 45° section of cryostat thus serves as reflector to turn vertical M beam emerging from SFHe surface into the horizontal

Muonium Gravity Experiment

- One can then imagine the following apparatus:



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$$S = \frac{1}{C\sqrt{N_0}}\frac{d}{2\pi}\frac{1}{\tau^2}$$
$$\approx 0.3\,\mathrm{g}\ \text{per}\ \sqrt{\#\text{days}}$$

where

C = 0.1 (est. contrast)

N_0 = # of events

d = 100 nm (grating pitch)

τ = M lifetime

VOLUME 71, NUMBER 15 PHYSICAL REVIEW LETTERS 11 OCTOBER 1993

Focusing a Beam of Ultracold Spin-Polarized Hydrogen Atoms with a Helium-Film-Coated Quasiparabolic Mirror

V. G. Luppov
Randall Laboratory of Physics, University of Michigan, Ann Arbor, Michigan 48109-1120 and Joint Institute for Nuclear Research, Dubna, Russia

W. A. Kaufman, K. M. Hill,* R. S. Raymond, and A. D. Krisch
Randall Laboratory of Physics, University of Michigan, Ann Arbor, Michigan 48109-1120

(Received 7 January 1993)

We formed the first "atomic-optics" beam of electron-spin-polarized hydrogen atoms using a quasi-parabolic polished copper mirror coated with a hydrogen-atom-reflecting film of superfluid ^{4}He. The mirror was located in the gradient of an 8-T solenoidal magnetic field and mounted on an ultracold cell at 350 mK. After the focusing by the mirror surface, the beam was again focused with a sextupole magnet. The mirror, which was especially designed for operation in the magnetic field gradient of our solenoid, increased the focused beam intensity by a factor of about 7.5.

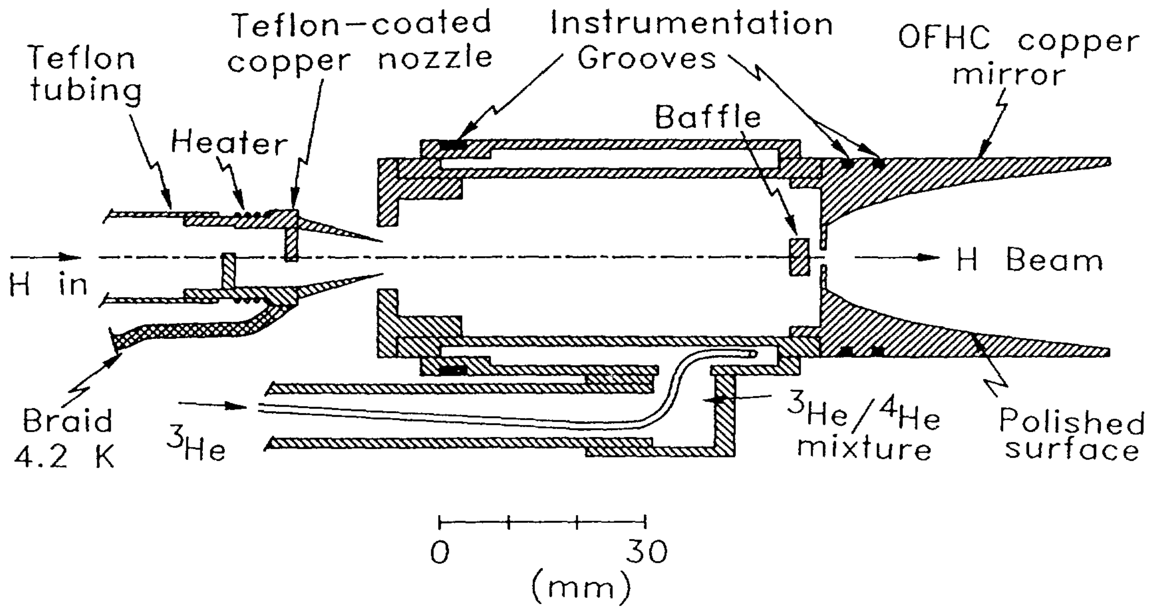
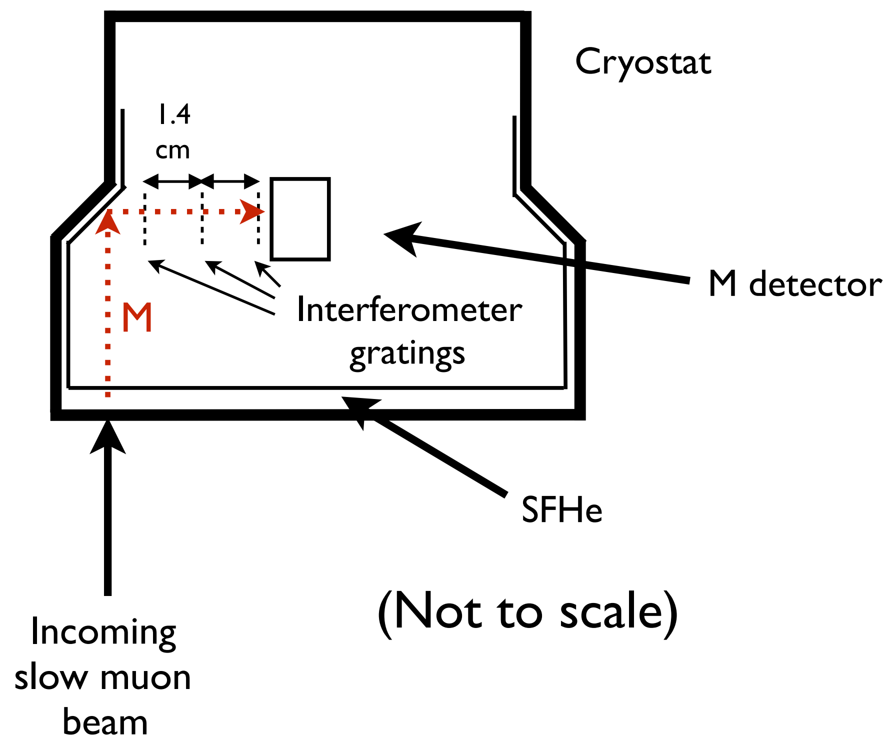


FIG. 2. Schematic diagram of the stabilization cell and mirror. The Teflon-coated copper nozzle is also shown.

- SFHe H mirror an established technique

Muonium Gravity Experiment

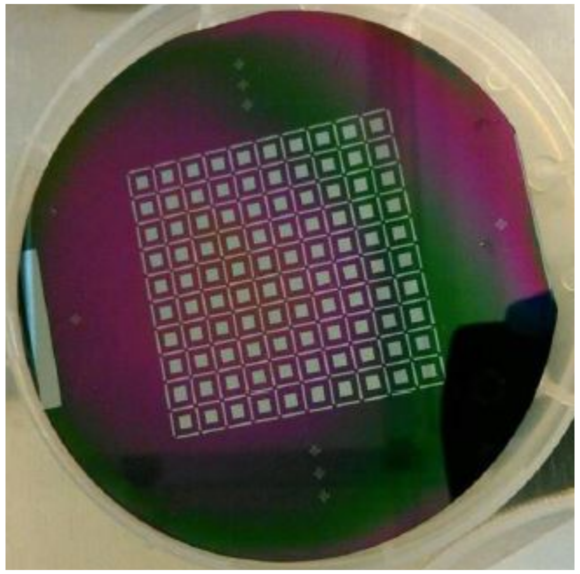
- Some important questions:



1. Can sufficiently precise diffraction gratings be fabricated?
2. Can interferometer be aligned to a few pm and stabilized against vibration?
3. Can interferometer and detector be operated at cryogenic temperature?
4. How determine zero-degree line?
5. Does Taqqu's scheme work?

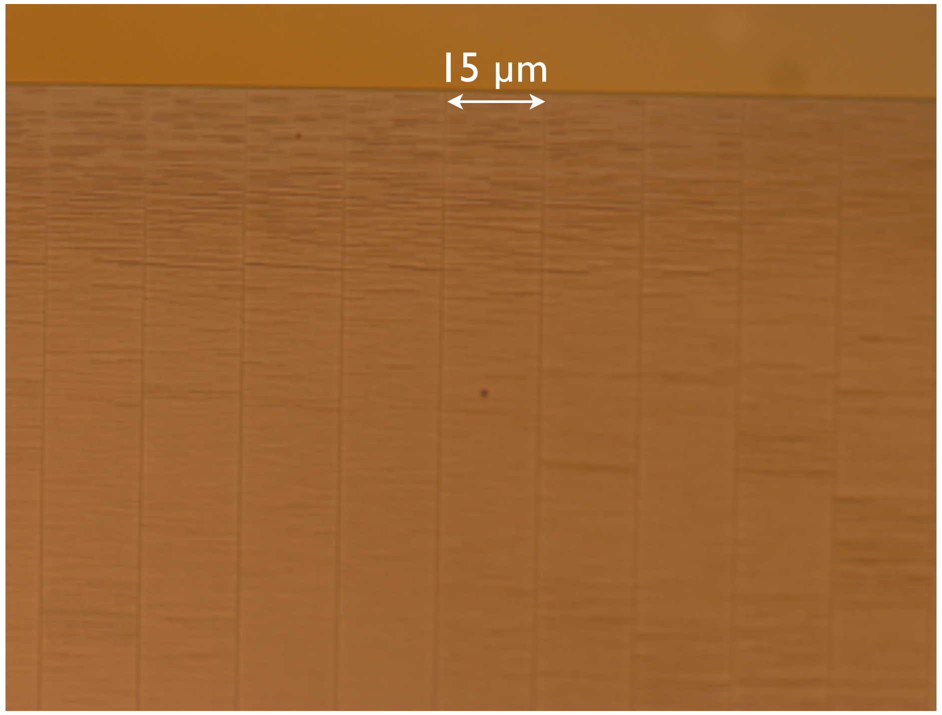
Answering the Questions:

1. Can sufficiently precise diffraction gratings be fabricated?
   - our collaborator, Derrick Mancini, formerly of ANL Center for Nanoscale Materials (CNM), thinks so – effort started at CNM

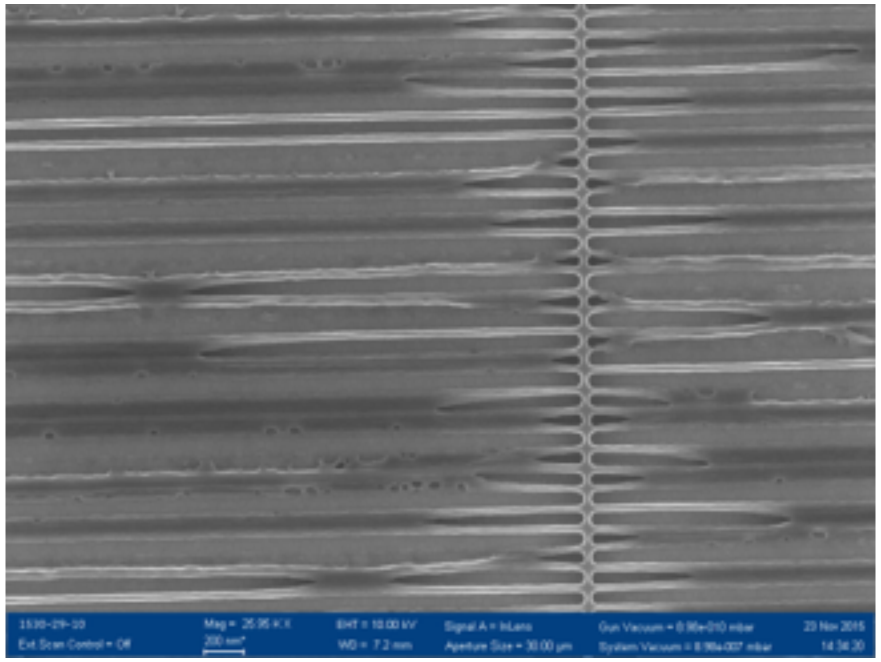


1st Si wafer with test gratings
1st resist applied &
e-beam exposed

Optical image:
resist
deformation



100 nm



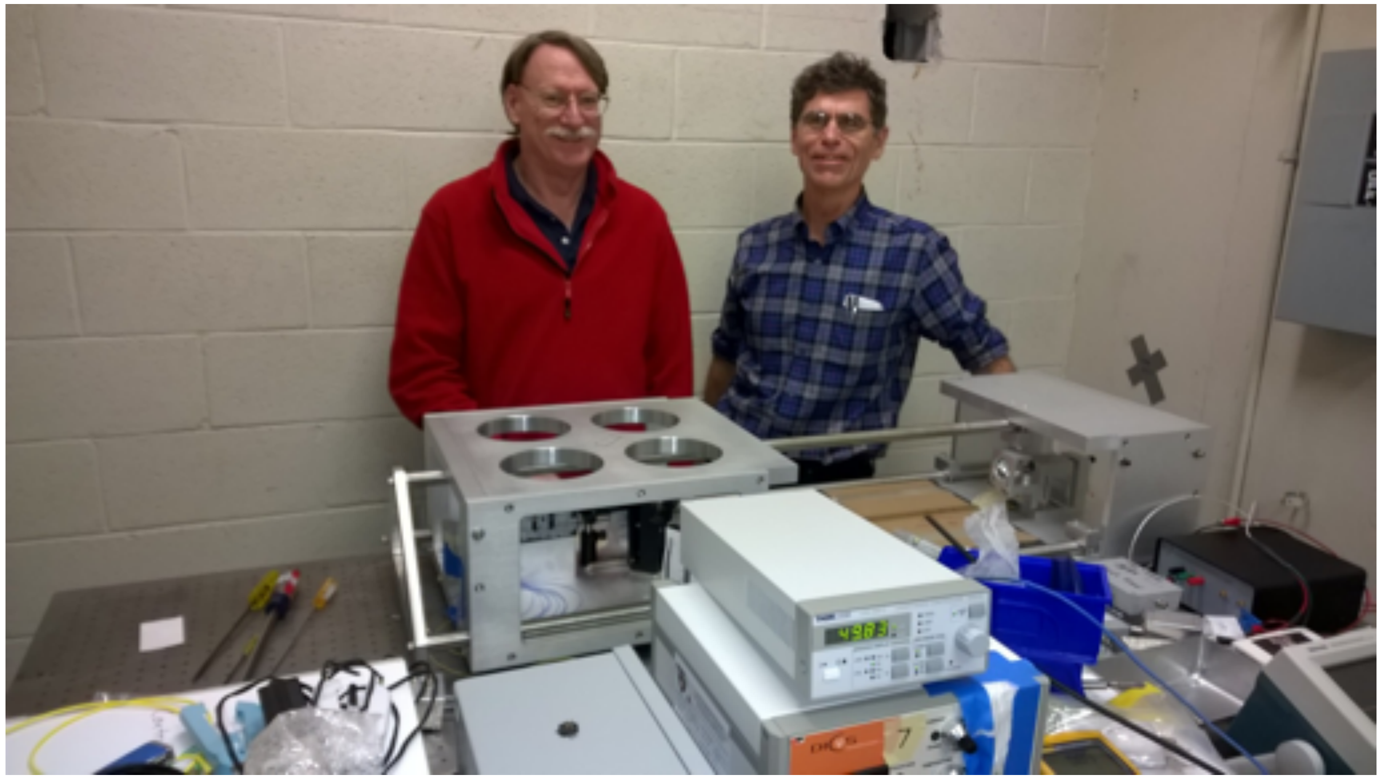
SEM image at higher magnification

(such things *always* require multiple iterations…)

Answering the Questions:

1. Can sufficiently precise diffraction gratings be fabricated?
   - our collaborator, Derrick Mancini, formerly of ANL Center for Nanoscale Materials (CNM), thinks so – effort started at CNM

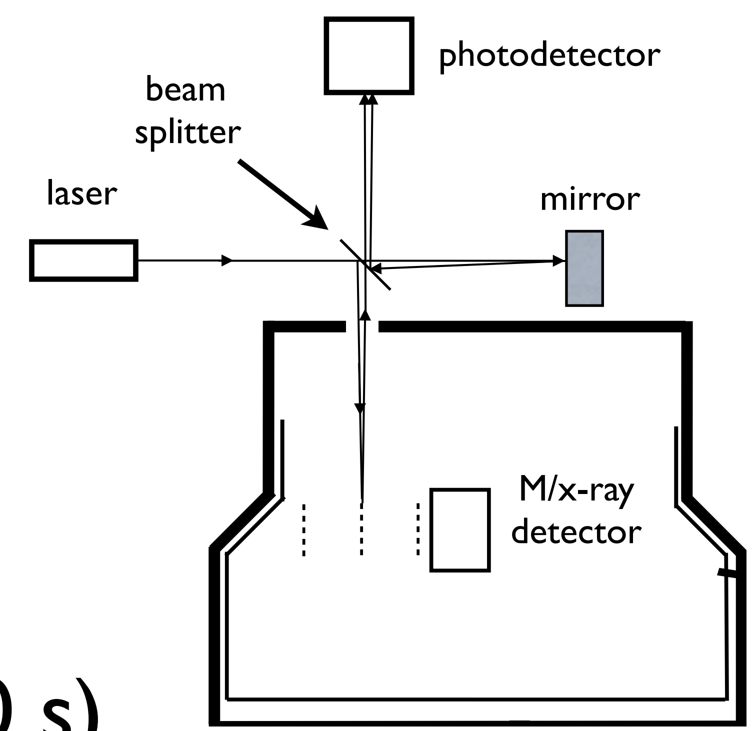
2. Can interferometer be aligned, and stabilized against vibration, to several pm?
   - needs R&D, but LIGO & POEM do *much* better than we need
   - we are setting up a POEM distance gauge (TFG) at IIT



Interferometer Alignment

- E.g., use 0/1/2 laser interferometers on 1st/2nd/3rd grating
  - need ~ 10 pm @ λ = 1560 nm, $\Rightarrow$ ~ 10^{-5} x smaller
    - shot-noise limit (1 μW) = 0.04 pm
    - 3 pm demonstrated (averaging over 100 s)
    - To do:
      - reduce laser power
      - demonstrate in appropriate geometry
      - use TFG to demonstrate stability of muonium interferometer structure…

Concept:



"Laser Tracking Frequency Gauge" (TFG)

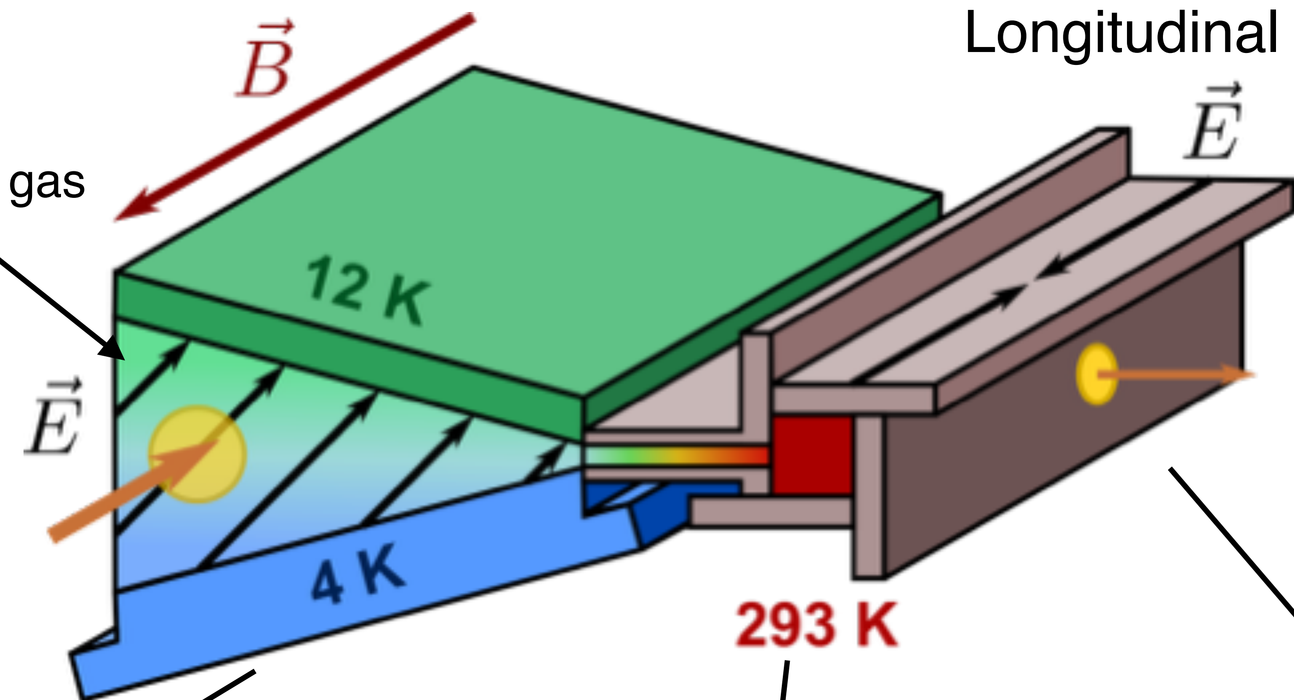
[R. Thapa et al., "Subpicometer length measurement using semiconductor laser tracking frequency gauge," Opt. Lett. **36**, 3759 (2011)]

Answering the Questions:

1. Can sufficiently precise diffraction gratings be fabricated?
   - our collaborator, Derrick Mancini, formerly of ANL Center for Nanoscale Materials (CNM), thinks so – effort in progress at CNM…
2. Can interferometer be aligned, and stabilized against vibration, to several pm?
   - needs R&D, but LIGO & POEM do much better than we need
   - we are setting up a POEM distance gauge (TFG) at IIT to try it
3. Can interferometer and detector be operated at cryogenic temperature?
   - needs R&D; at least piezos OK; material properties favorable
4. How determine zero-degree line?
   - use cotemporal x-ray beam (detected how well by M detector?)
5. Does Taqqu's scheme work?
   - needs R&D; we're working on it with PSI

Experimental Tests in Stages

PAUL SCHERRER INSTITUT



Secondary μ⁺ beam
D ≈ 10 mm
E ≈ 4 MeV
continuous
polarized

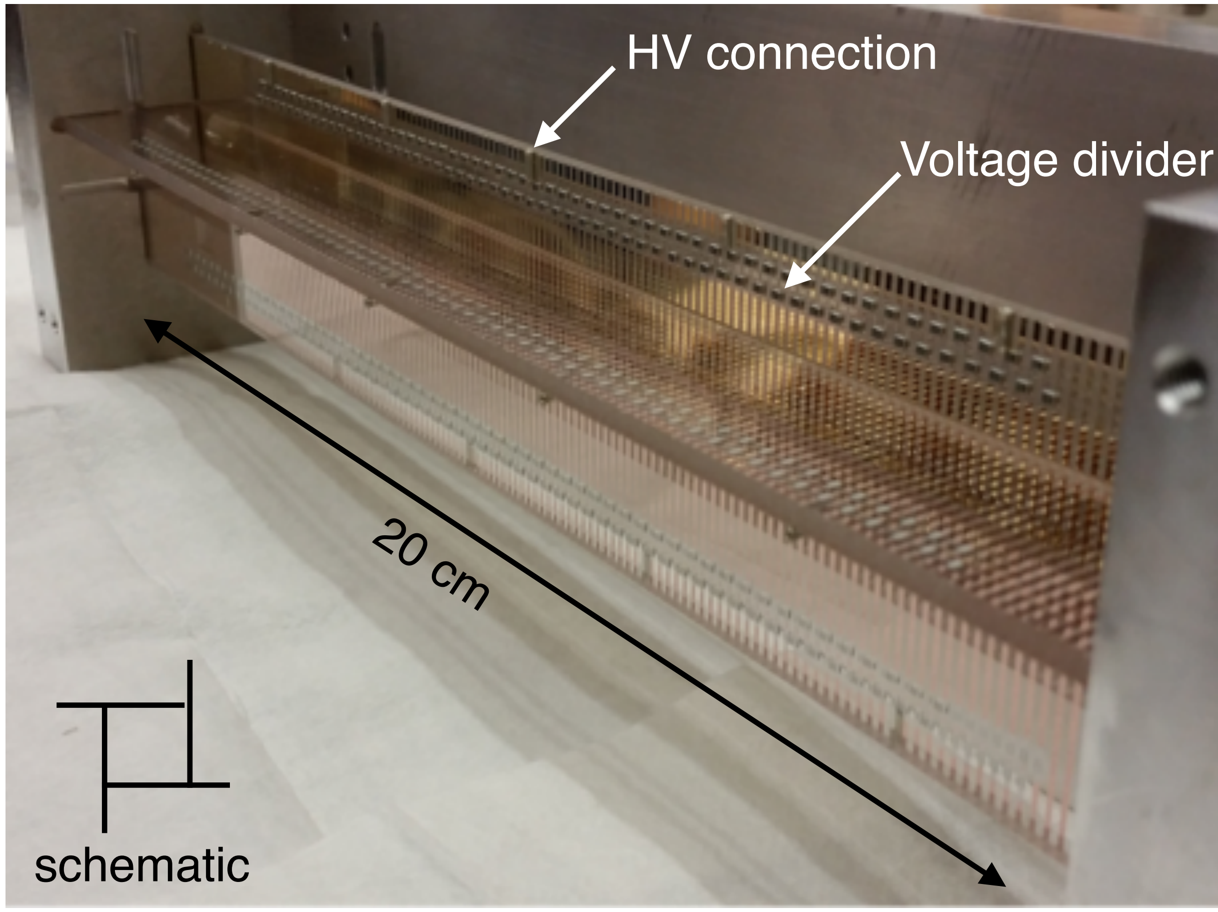
Tertiary μ⁺ beam
D < 1 mm
E < 1 eV
pulsed, tagged
polarized

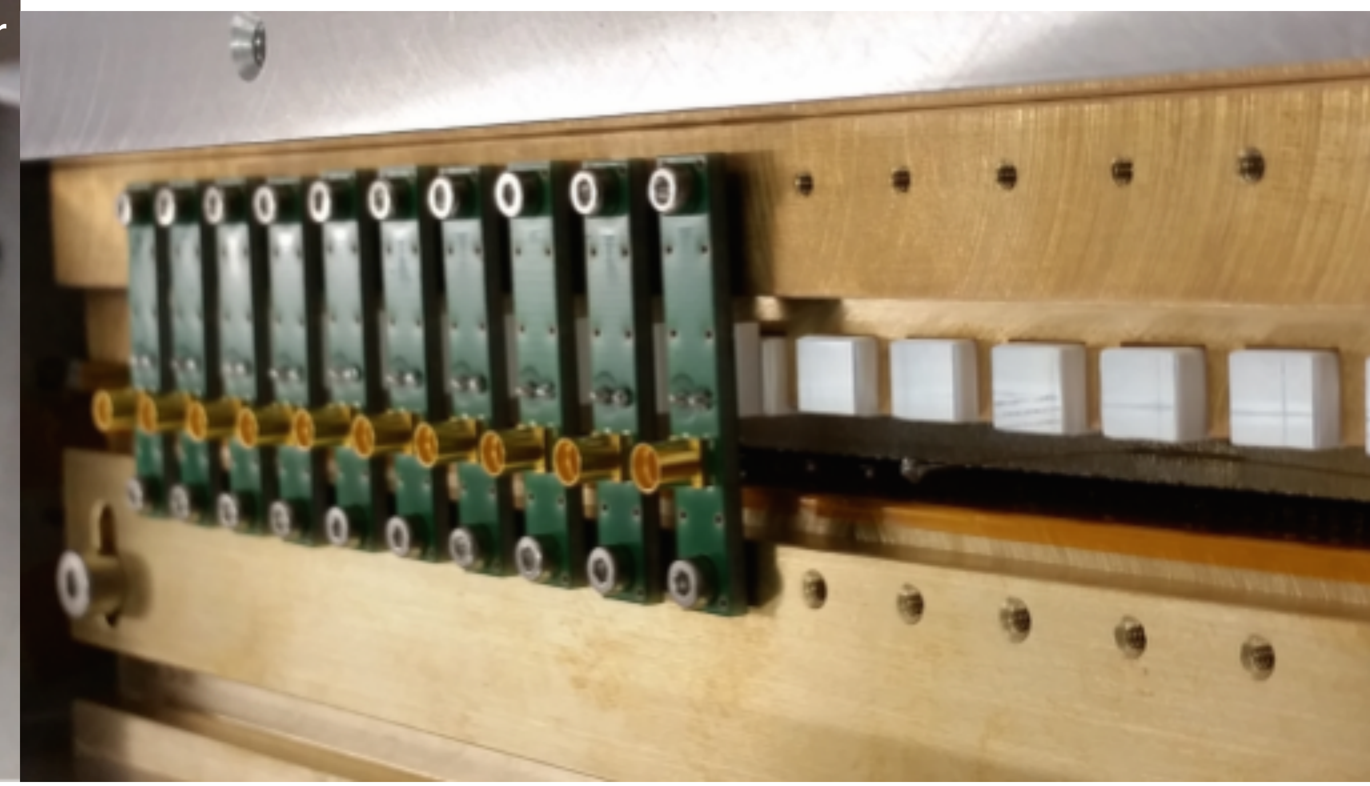
Transverse compression:
- First experimental test in Dec. 2014
- Improved tests in Dec. 2015

Longitudinal compression:
- First experimental test in 2011
- Improved tests in Dec. 2014

Extraction into vacuum:
- Under development

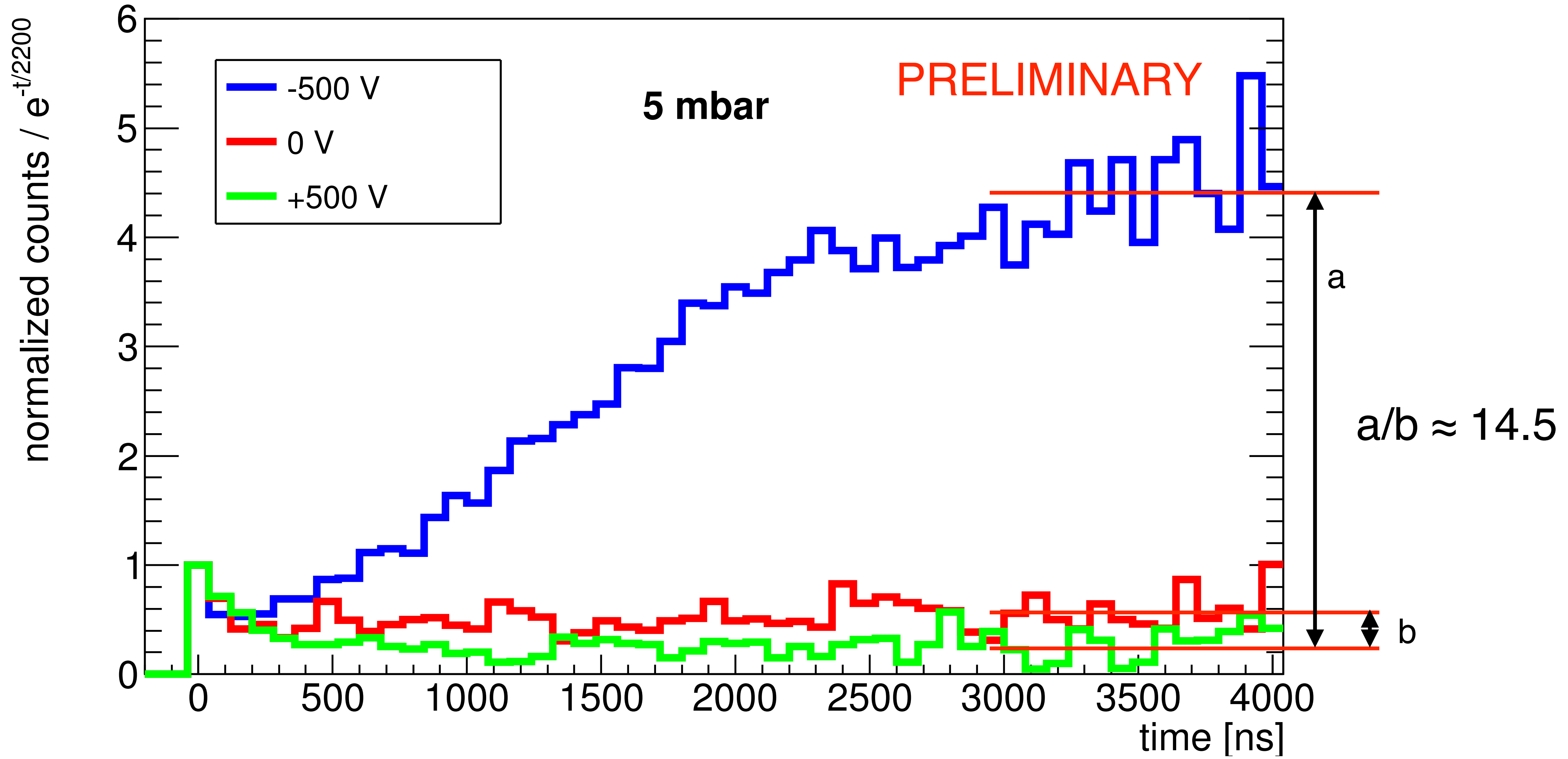
Improved Setup





- Improved cleanliness of target → no chemical absorption
- Better shielding of detectors, larger volume → less background
- More scintillators (26) → observe temporal evolution of the compression
- Scintillators in telescope configuration → high spatial sensitivity at center

Results of Improved Setup



- Compression efficiency ~ a/b
- From simulation: (100 ± xx)% compression

Additional Considerations

- What's the optimal muonium pathlength?
  - say double muonium interferometer baseline: $L \rightarrow 2\nu\tau$ costs $e^{-2} = 1/7.4$ in event rate, but gains x 4 in deflection
    - a net win by $4\,e^{-1} \approx 1.5$ → Statistically optimal!
  - OTOH, tripling baseline → x 1.2 improvement w.r.t. $\nu\tau$
    - still better than 1 lifetime, but diminishing returns
    - *but* — 9 x bigger signal ⇒ easier calibration, alignment, & stabilization

- Need simulation study to identify *practical* optimum, taking all effects into account

Prospects

- To do the experiment we need a grant!
  - to get a grant we need a track record of accomplishment!
    - but nobody's ever done this before!

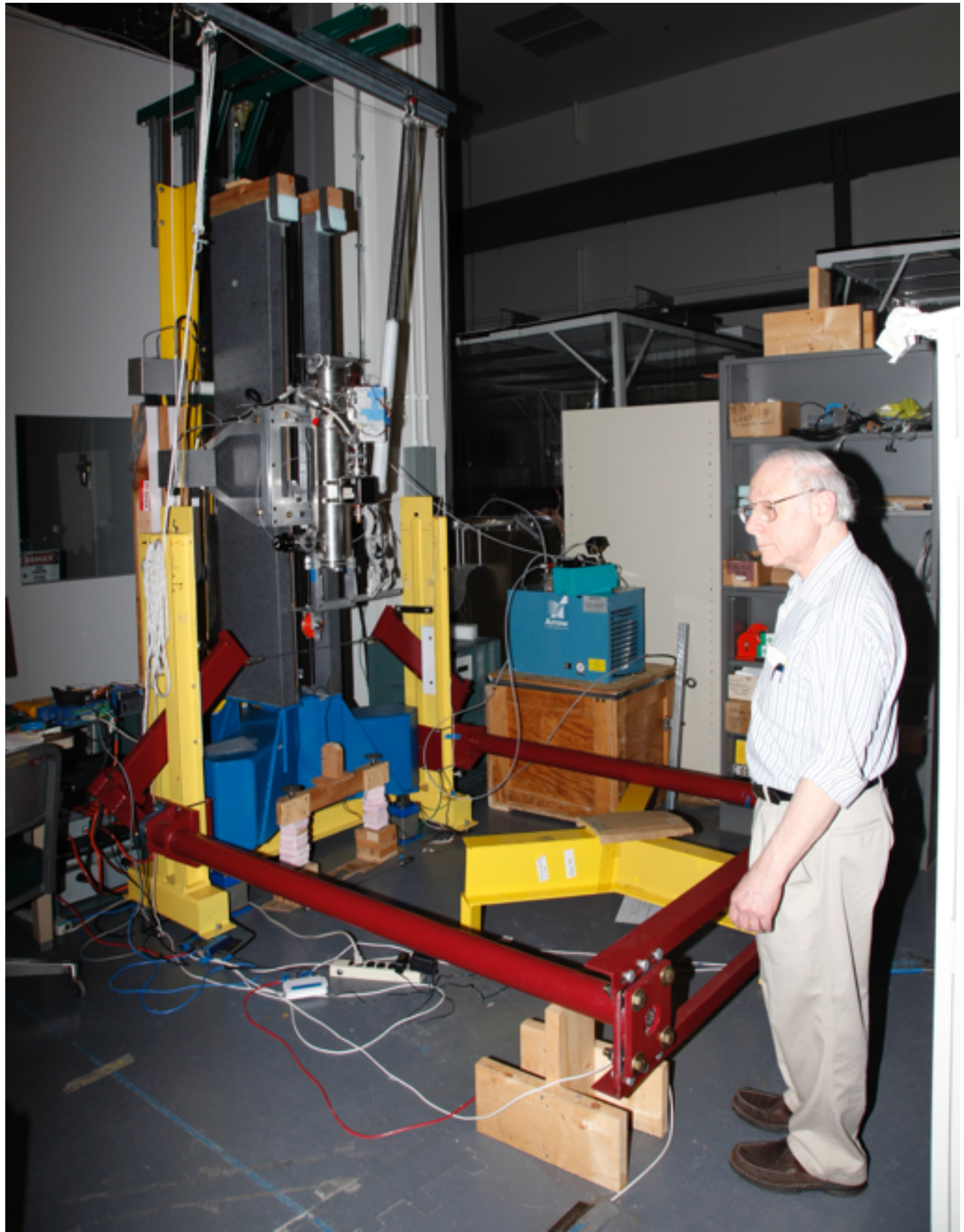
➡ how break out of the loop?

- IIT IPRO & BSMP programs

Prospects

- Moreover, we're the beneficiaries of the POEM program at Harvard-Smithsonian CfA
  - built to test Equivalence Principle via picometer measurement of distance between 2 dissimilar test masses in free fall
  - including 2 TFGs
  - so we have opportunity to demonstrate expertise!
  - as well as to continue to develop G-POEM with IPRO teams of undergrads

G-POEM @ CfA



G-POEM @ IIT

Progress

- IPROs (as well as Brazilian Scientific Mobility Program summer students) have been productive
  - accomplishments:
    - Mathematica and C codes to model 3-grating interferometer (signal)
    - G4beamline code to model interferometer and detector geometry and materials (backgrounds)
    - FEA modeling of thermo-mechanical properties of interferometer bench and gratings begun
    - prototype grating layouts in e-beam litho @ CNM
    - setup of new lab space @ IIT

Collaborators

- Jim Phillips, ex-Harvard-Smithsonian CfA
- Bob Reasenberg, ex-Harvard-Smithsonian CfA
- Derrick Mancini, ex-ANL CNM, adjunct at IIT
- Tom Phillips, ex-Duke, adjunct at IIT
- Tom Roberts, Muons, Inc., adjunct at IIT
- Jeff Terry, IIT
- Klaus Kirch, PSI and ETH Zurich
- Ephraim Fischbach, Purdue

Conclusions

- Antigravity hypothesis might neatly solve several vexing problems in physics and cosmology
  - or $\overline{g} = g \pm \varepsilon$ may point the way to a deeper theory
- In principle, testable with antihydrogen *or* muonium (or positronium?)
  - if possible, *all* should be measured — *especially* if $\overline{\mathrm{H}}$ found anomalous

➡ First measurement of muonium gravity would be a milestone!

- But 1st, must determine feasibility — in progress!

Final Remarks

- These measurements are a required homework assignment from Mother Nature!

- Whether $\overline{g} = -g$ or not, if successfully carried out, the results will certainly appear in future textbooks.

BACKUPS

Do we need to test the POE?

- Many argue not – Eötvös/Eöt-Wash, earth-moon-sun system,…"set limits $\mathcal{O}(10^{-[7-9]})$"*
- But these arguments *all* rest on *untested assumptions* – e.g. [Alves, Jankowiak, Saraswat, arXiv:0907.4110v1]

  "We then make the assumption that any deviation of g_{H} from $g_{\bar{\mathrm{H}}}$ would manifest itself as a violation of the equivalence principle in these forms of energy† at the same level."

- Aren't such assumptions worth testing???
  - especially when doing so costs ≪ LHC?
  - and so much is potentially at stake?

* in any case, these don't apply to muons

† i.e., fermion loops and sea antiquarks